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IMPULSE DRYING OF RECYCLED MULTI-PLY LINERBOARD: LABORATORY-SCALE STUDIES

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ABSTRACT

Laboratory-scale impulse drying simulations have been conducted to identify important pulp substitution variables and quantify the benefit of impulse drying for multi-ply linerboard manufactured with recycled furnishes.

Single-ply 42 lb liner made from five minimally refined furnishes were impulse dried to explore the influence of fiber species and lignin content on impulse drying. Kappa number was found to have little effect on impulse drying performance, while southern pine was found to have an advantage over Douglas fir.

Single-ply liner was also made from various blends of recycled OCC with virgin Kraft. A strength advantage of impulse drying was observed at recycle concentrations of 50 percent or less, while a dryness advantage was observed for blends having recycle concentrations of 75 percent or less.

Two-ply sheets of various constructions were impulse dried to determine how the composition of the top and bottom layer influence optimum impulse drying operating conditions and resulting dryness and physical properties. It was discovered that the composition of that part of the sheet in contact with the heated surface controls the critical impulse drying temperature. When the bottom sheet was composed of 50 percent virgin southern pine Kraft and 50 percent recycled OCC fiber, superior impulse drying dryness and physical property development were observed for top sheet compositions having freenesses of 450 ml CSF or more. Sheets constructed with a bottom sheet of recycled OCC fiber and a top sheet of virgin southern pine Kraft showed enhanced dryness and strength as long as the heated surface of the sheet had a freeness of 600 ml CSF or more.

INTRODUCTION AND EXPERIMENTAL DESIGN

Ongoing laboratory and pilot-scale research at the Institute of Paper Science and Technology (IPST) has demonstrated that heavy weight grades of paper, such as linerboard, can be successfully impulse dried (1-15). That research has shown that deleterious sheet delamination can be avoided by a combination of processing strategies. These strategies include steps to make the prepressed sheets highly permeable to water flow and steps to reduce excess heat transfer to the sheet that results in excessive internal flash evaporation at the exit of the impulse dryer.

Research at IPST suggests that high sheet darcian permeability (low hydrodynamic specific surface) can be obtained by limiting refining to the minimum required for product aesthetics and by prepressing the sheet to as high a solids as possible. In addition, IPST research suggests that excessive pressure dependent heat transfer can be eliminated by using press roll surfaces composed of materials having low thermal conductivity, low heat capacity, and low density.

Previous IPST research was conducted with single-ply linerboard sheets composed of virgin southern pine that was minimally refined to eliminate shives. In contrast, commercial linerboard is usually two or three ply and composed of blends of virgin Kraft and recycled fiber. While current recycle content varies from mill to mill, there is increasing environmental pressure to increase recycle content. Mills in the U.S. typically use recycled fiber from old corrugated containers which are collected at warehouses and other high volume locations. In current practice, the amount of recycled fiber included in linerboard is limited by the fact that sheet strength properties decrease when recycle content is increased. To acheieve acceptable strength, mills either limit recycle content or further refine the recycle fiber which negatively impacts water removal and machine speeds. Recycled fiber has the additional disadvantage in that it has an unacceptable physical appearance. To improve the appearance of liner, made with recycle fiber, U.S. manufacturers form a multi-ply sheet where recycled fiber is contained in a bottom or inner layer, and outer layers are made from virgin Kraft sufficiently refined to impart a good appearance to the product.

The present research was designed to extend impulse drying to sheet constructions that correspond to commercial sheet structures. The experimental program was conducted in three experimental groups based on the sheet structures as shown in Figure 1.

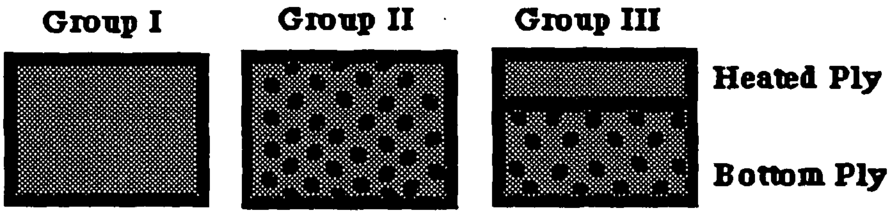

Figure 1. Schematic of Sheet Structures.

Table 1 shows the composition of sheets in each of these groupings. In the first grouping, pulp species and Kappa number were investigated. In the second grouping, blends of virgin and recycled OCC were investigated. While in the third group of experiments, the influence of the composition and freeness of both heated and bottom plies were investigated. In all cases, the total basis weight of the sheets was kept at 205 g/m^2.

In previous research, sheet delamination has been shown to begin at a critical temperature that depends on the hydrodynamic specific surface of the sheet to be impulse dried. Hydrodynamic specific surface, in turn, is expected to be a function of fiber dimensions and extent of prepressing (10). Therefore, for each of the sheet compositions listed in Table 1, fiber dimensions and hydrodynamic specific surface were determined from sheet samples with the intent that these measurements would be useful in predicting critical temperature.

Table 1. Sheet Composition.

Group	Heated Ply				Bottom Ply			
	Wt. % of Total	Species or Type	Kappa No.	Freeness ml CSF	Wt. % of Total	Species or Type	Kappa No.	Freeness ml CSF
I	100	D. Fir	HIGH	HIGH	--------	--------	--------	--------
	100	D. Fir	LOW	HIGH	--------	--------	--------	--------
	100	S. Pine	HIGH	HIGH	--------	--------	--------	--------
	100	S. Pine	LOW	HIGH	--------	--------	--------	--------
	100	OCC	HIGH	HIGH	--------	--------	--------	--------
	100	OCC	HIGH	LOW	--------	--------	--------	--------
II	25 75	S.Pine OCC	HIGH HIGH	HIGH HIGH	--------	--------	--------	--------
	50 50	S.Pine OCC	HIGH HIGH	HIGH HIGH	--------	--------	--------	--------
	75 25	S.Pine OCC	HIGH HIGH	HIGH HIGH	--------	--------	--------	--------
	50 50	S.Pine OCC	HIGH HIGH	HIGH LOW	--------	--------	--------	--------
III	20	S. Pine	HIGH	HIGH	40 40	S.Pine OCC	HIGH HIGH	HIGH HIGH
	20	S. Pine	HIGH	MED	40 40	S.Pine OCC	HIGH HIGH	HIGH HIGH
	20	S. Pine	HIGH	LOW	40 40	S.Pine OCC	HIGH HIGH	HIGH HIGH
	20	S. Pine	HIGH	HIGH	80	OCC	HIGH	HIGH
	20	S. Pine	HIGH	LOW	80	OCC	HIGH	HIGH

EXPERIMENTAL METHODS

Sheet Forming

The Formette Dynamique was chosen to fabricate handsheets in order to provide multi-ply machine direction oriented sheets. Preliminary experiments were conducted with unbleached high Kappa southern pine (HKSP) to determine the correct Jet-to-Wire ratio (JWR) to produce handsheets with a two-to-one, MD-to-CD tensile ratio.

Toward this end, the jet velocity was fixed at 316 m/min, while the wire velocity was varied to obtain JWR of 0.3 to 0.4. To simplify the pressing procedures, sheets were drained at a constant wire speed of 1050 m/min.

HKSP refined to three levels of freeness were formed at various JWRs, drained at constant speed, and conventionally pressed to 52% solids. Samples of these sheets were then tested to determine their darcian permeability as reported in terms of hydrodynamic specific surface. Figure 2 shows that specific surface was decreased by reduced refining, while being relatively insensitive to JWR. Samples were also cylinder dried, conditioned, and tested for MD and CD tensile strength. The MD/CD tensile ratio of these specimens is plotted as a function of JWR in Figure 3. As commercial liner typically has an MD/CD tensile ratio of about 2, subsequent experiments were conducted with sheets formed at a constant JWR of 0.4 corresponding to a wire speed of 800 m/min.

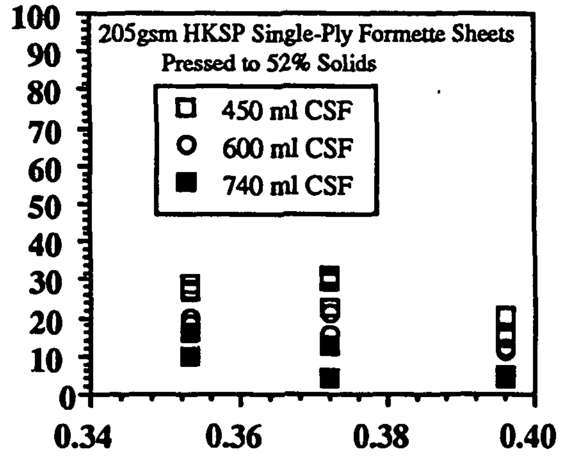

Figure 2. Hydrodynamic specific surface as a function of Jet-to-Wire velocity ratio for sheets pressed to 52% solids.

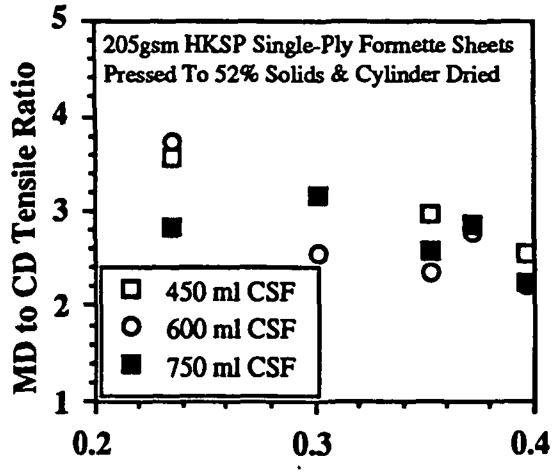

Figure 3. MD-to-CD tensile ratio as a function of Jet-to-Wire velocity ratio.

Fiber Dimensions Measurement

Samples of sheets prepared for impulse drying and double-felted pressing were coded and sent to John D. Hankey & Associates of Appleton, Wisconsin, for fiber species identification, fiber length, fiber width, cell wall thickness, and coarseness measurements.

Table 2 shows the results of the species identification for the furnish components used in the present research.

Table 2.
Fiber Identification For Various Pulp Samples.

Pulp Type	USW K %	UHW K %	Softwood Species	Hardwood Species
S.Pine High Kappa	98	2	Southern yellow pine (Hard Cook)	Mixed, incl. Poplar
S.Pine Low Kappa	100(-)	trace	Southern yellow pine (Soft, Medium, & Hard Cook)	Mixed, incl. Gum
D.Fir High Kappa	99	1	40-50% Douglas Fir 40-50% Ponderosa or Lodgepole pine 5-10% Balsam Fir, 1% Western Hemlock 1% Engelman Spruce, 1% Western Pine 1% Western Red Cedar (Hard Cook)	Alder
D.Fir Low Kappa	99	1	70-80% Douglas Fir 5-10% Ponderosa or Lodgepole pine 5-10% Balsam Fir, 5% Western Red Cedar 5% Engelman Spruce, 1% Western White Pine, 1% Western Larch (Hard Cook)	Mixed, incl. Alder and Maple
OCC	76	24	80-90% Southern Yellow Pine 5-10% Douglas Fir, 1% Balsam Fir, 1% White and/or Red Pine, 1% Hemlock (53% Hard Cook, 18% Medium Soft Cook)	Mixed, incl. 20-30% Gum, 20-30% Oak, 10-20% Populus Sp., 10-20% Yellow Poplar, 5% Maple, 5% Elm, 5% Basswood, 5% Cherry, 5% Sycamore

Each of these furnishes were refined to various freeness levels and formed into 205 g/m^2 sheets. Table 3a and 3b summarize the average fiber dimensions.

Table 3a.
Fiber Dimensions for Group I Sheets.
(Single Furnish/ Single-Ply 205 g/m^2 Sheets Made on the Formette Dynamique)

Pulp Type	Kappa No.	Freeness ml CSF	Length mm			Width mm	Perimeter mm	Cell Wall Thickness mm	Coarseness mg/100 m
			Arith	LW	WW				
S.Pine	109.2	450	1.66	2.29	2.90	38.4	88.4	2.9	34.6
	(High)	600	1.77	2.47	3.11	40.7	93.0	2.9	35.6
		750	2.48	3.19	3.74	40.3	92.6	3.0	34.0
S.Pine	63.4	450	1.88	2.64	3.31	38.3	88.6	3.0	30.4
	(Low)	600	1.86	2.54	3.17	39.7	91.0	2.9	29.6
		710	2.60	3.29	3.78	41.5	92.2	2.3	30.8
D.Fir	89.6	450	1.20	1.59	2.00	35.8	80.4	2.2	23.2
	(High)	600	1.28	1.75	2.19	37.5	83.4	2.1	24.0
		720	2.02	2.69	3.20	38.3	85.8	2.3	23.8
D.Fir	74.2	450	1.44	2.05	2.59	37.0	84.0	2.5	25.6
	(Low)	600	1.75	2.38	2.89	39.1	87.8	2.4	25.2
		710	2.15	2.80	3.32	39.3	87.4	2.2	25.6
OCC	114.6	450	1.33	1.88	2.57	27.8	66.0	2.6	25.8
	(High)	600	1.54	2.20	2.93	29.2	68.8	2.6	24.8

Table 3b.
Fiber Dimensions for Group III Sheets.
(Two Furnish/Two-Ply 205 g/m^2 Sheets Made on the Formette Dynamique)

Wt. % HKSP 750 ml CSF in Bot.Ply	Wt. % OCC 600 ml CSF in Bot. Ply	Freeness of HKSP Heated Ply ml CSF	Length mm			Width mm	Perimeter mm	Cell Wall Thickness mm	Coarseness mg/100 m
			Arith	LW	WW				
40	40	450	1.81	2.56	3.28	34.9	81.0	2.8	31.4
40	40	600	1.63	2.51	3.38	32.9	77.8	3.0	32.0
40	40	750	1.95	2.78	3.46	31.9	76.2	3.1	31.8
0	80	450	1.51	2.24	2.99	30.0	71.6	2.9	27.0
0	80	750	1.58	2.47	3.34	32.1	75.8	2.9	26.2

Hydrodynamic Specific Surface Measurements

Transverse permeability measurements were made using equipment and techniques that have been previously presented (10). In this method, Darcian permeability coefficient versus porosity data are used to determine the hydrodynamic specific surface of a saturated sheet. While the resulting hydrodynamic specific surface is related to fiber geometry it is also influenced by formation, basis weight and pressing effects. In the experiments of this study basis weight, formation and pre-pressing (to 50% ingoing solids) were held constant. Hence, the hydrodynamic specific surface data was expected to be directly related to fiber geometry.

Double-Felted Pressing and Impulse Drying Simulations

Figure 4 shows a schematic of the electrohydraulic press used to simulate double-felted pressing and impulse drying. The apparatus was designed to simulate the transient mechanical and thermal conditions experienced during these processes. A newly installed programmable signal generator allowed the electrohydraulic press to simulate a pressure history that the sheet would experience in a commercial impulse dryer configured on a long-nip shoe press. For impulse drying simulations, thermal conditions were simulated using a ceramic-coated platen heated to the operating temperature of the process.

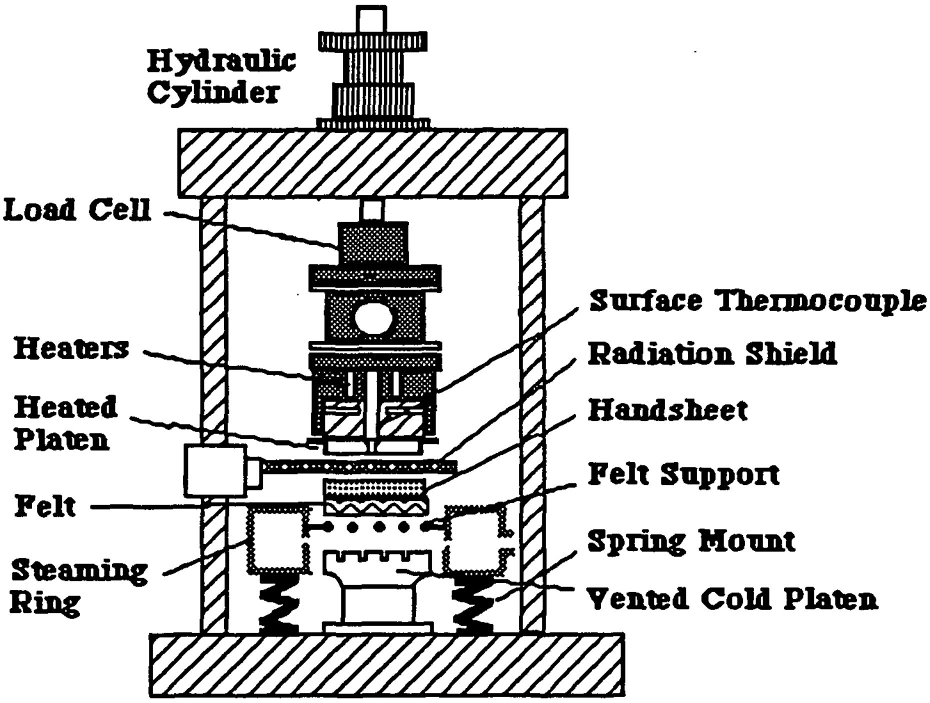

Figure 4. Schematic of the Electrohydraulic Press.

In impulse drying experiments, wet sheets of paper on felts were placed onto a wire support attached to a steaming ring. A radiation shield was automatically positioned between the heated platen and the sheet to reduce dry-out of the top surface of the sheet. Steam exiting from the ring flowed upward through the felt and the sheet. By controlling steam pressure and adjusting the steaming time, the initial temperature in the sheet was raised to 85°C. Once the sheet was heated, the hydraulic system was activated to give a pressure pulse of 40 millisecond duration simulating an 8500 pli load on a "0" pivot shoe press.

Double-felted pressing experiments were conducted in a similar manner, except that the platen was maintained at 100°C, and the wet sheet was sandwiched between two identical felts. For both double-felted pressing and impulse drying, the initial wet weight of the paper sheet was adjusted so that the ingoing dryness of the sheet after steam preheating was 52% solids +/- 2%. This required that water weight loss during steam pre-heating be calibrated as a function of initial platen temperature for each furnish. Ingoing felt moisture was kept at 16 percent.

EXPERIMENTAL RESULTS

Hydrodynamic Specific Surface

In this section, the out-of-plane permeability of single and two component single-ply sheets will be presented. Figures 5 and 6 show the hydrodynamic specific surface of single component single-ply sheets as a function of their Canadian standard freeness. Figure 5 shows that high Kappa southern pine (HKSP) tended to be more permeable at a given freeness than low Kappa southern pine (LKSP). In contrast, the low Kappa Douglas fir (LKDF) shown in Figure 6 was more permeable than high Kappa Douglas fir (HKDF). Contrasting the southern pine and Douglas fir at high freeness, it was observed that the southern pine tends to be more permeable.

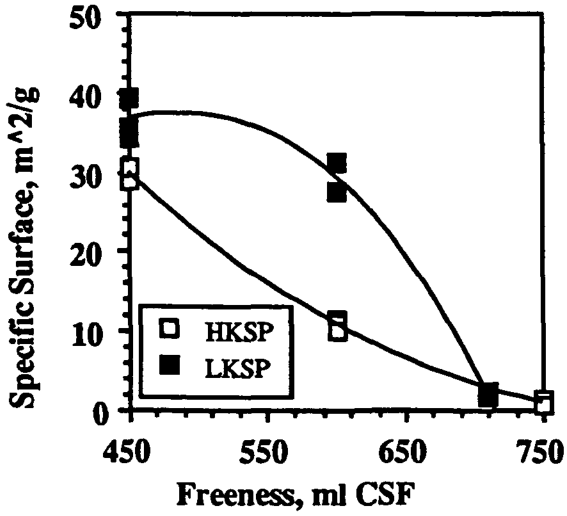

Figure 5. Specific surface vs. freeness for southern pine Kraft.

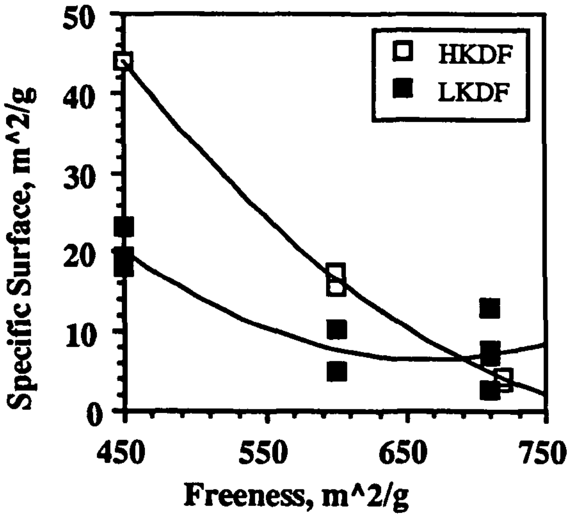

Figure 6. Specific surface vs. freeness for Douglas fir Kraft.

Similarly, hydrodynamic specific surface vs. freeness is shown for the OCC furnish in Figure 7. The specific surface of two component blends of high Kappa southern pine with OCC is shown as a function of the OCC content in Figure 8. It is of interest to note from Figure 8 that specific surface was not a linear function of OCC content. Hence, as much as 60% OCC by weight can be added to the blend without the hydrodynamic specific surface increasing beyond 5 m^2/g.

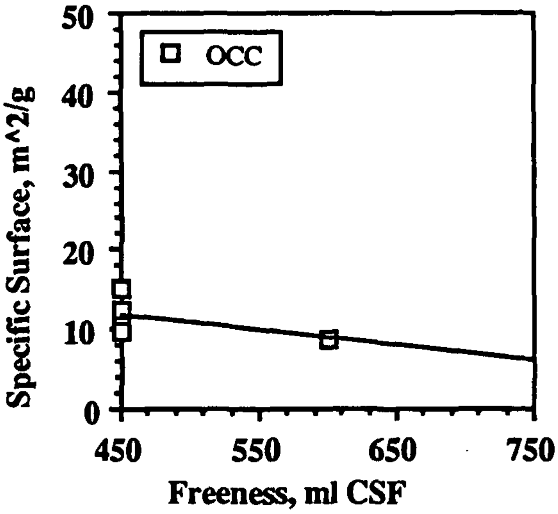

Figure 7. Specific surface vs. freeness for OCC.

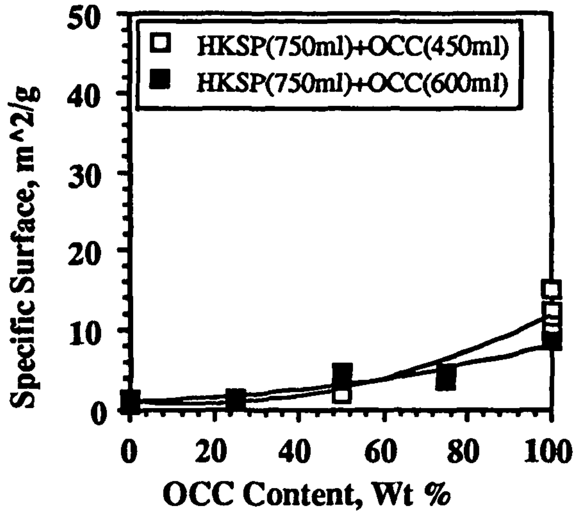

Figure 8. Specific surface vs. OCC content for single ply-blends of southern pine and OCC.

It was also observed that with single-ply linerboard, that was impulse dried (see Table 1), hydrodynamic specific surface was a linear function of the weight weighted fiber length that made up the sheet. This relationship is shown in Figure 9. It should be recalled that weight weighted fiber length is primarily a function of the fines concentration. Hence, sheet permeability was primarily influenced by fines concentration.

Critical Temperature

Previous research has shown that critical impulse drying temperature, defined as the platen temperature above which sheet delamination occurs, decreases with increasing hydraulic specific surface. That work, with single-ply sheets made from a single furnish, also showed that the benefits of impulse drying decreased as the critical temperature decreased.

As in previous work, critical temperatures have been determined by visual inspection and interpretation of out-of-plane ultrasound (specific elastic modulus) data and STFI compression strength data. The procedure was to define the critical temperature as the lowest temperature that showed no signs of delamination. The specific elastic modulus and its coefficient of variation are typically the most sensitive indicators. The coefficient of variation of the elastic modulus and its mean value were plotted against initial platen surface temperature. Delamination occurs when the coefficient of variation suddenly rises or when the modulus suddenly drops with increased initial platen temperature. In Figure 10, the critical temperature for the present experiments is plotted as a function of hydrodynamic specific surface. For single-ply sheets, the hydrodynamic specific surface was the measured value as per Figures 5 through 8. For two-ply sheets, the hydrodynamic specific surface was taken to be that of the surface of the sheet in contact with the heated platen. Data from previous work on the Institute's pilot roll press (12) are also shown for comparison in Figure 10.

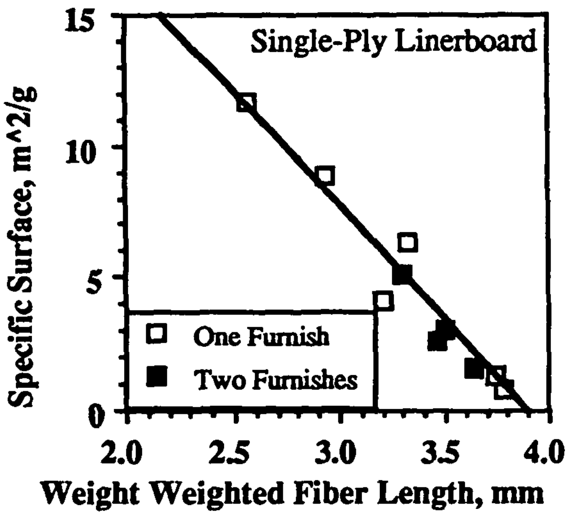

Figure 9. Hydrodynamic specific surface vs. weight weighted fiber length for single-ply linerboard pressed to 52% solids.

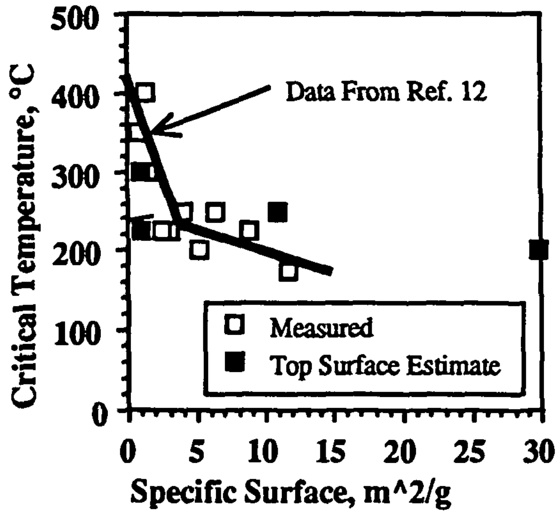

Figure 10. Critical impulse drying temperature vs. hydrodynamic specific surface for single- and double-ply linerboard.

The fact that the double-ply and single-ply data are consistent demonstrates that it is the hydrodynamic specific surface of the layer in contact with the heated platen (the top layer) that controls delamination.

The effect on critical temperature of increasing the concentration of OCC in a blend with HKSP is shown in Figure 11. It is observed that critical temperature decreases with increasing OCC content. The influence of the permeability of the layer in contact with the heated platen surface is again observed in Figure 12, where critical temperature increases when the extent of refining is reduced (i.e., higher freeness).

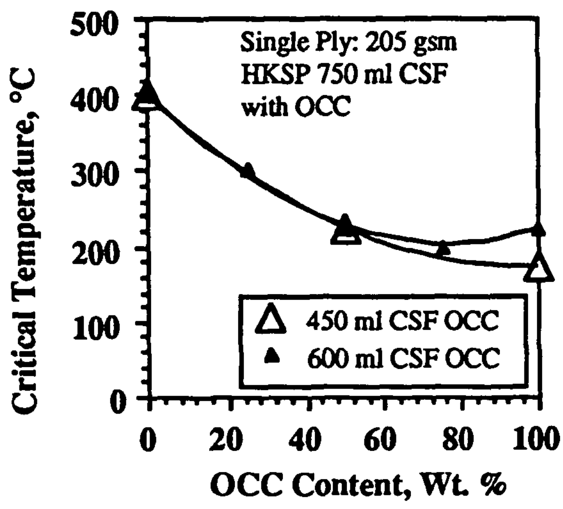

Figure 11. Critical impulse drying temperature vs. OCC content for single-ply sheets.

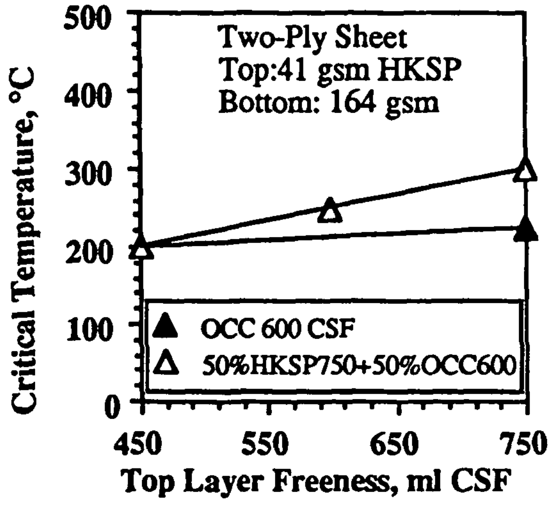

Figure 12. Critical impulse drying temperature vs. top layer freeness for double-ply sheets.

Impulse Drying vs. Double-felted Pressing

In this section, impulse drying at the critical temperature is compared to double-felted pressing and to a control that was pressed to 52% solids and cylinder dried. Figures 13 and 14 show outgoing solids vs. OCC content for single-ply sheets made from high Kappa southern pine and old corrugated containers. It is observed that impulse drying has a press dryness advantage over double-felted pressing for OCC content below 60%.

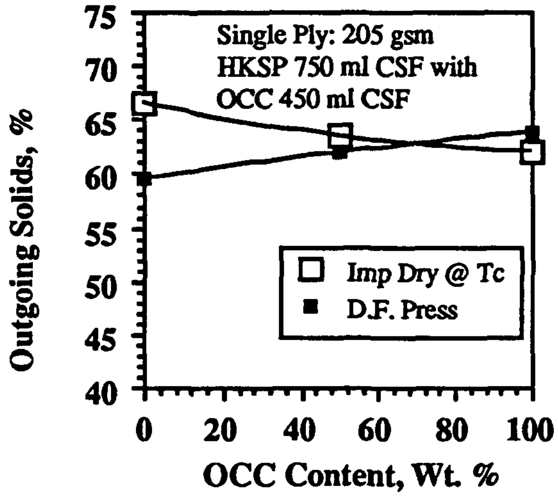

Figure 13. Outgoing solids vs. OCC content for impulse drying and double-felted pressing with blends of HKSP750 and OCC450.

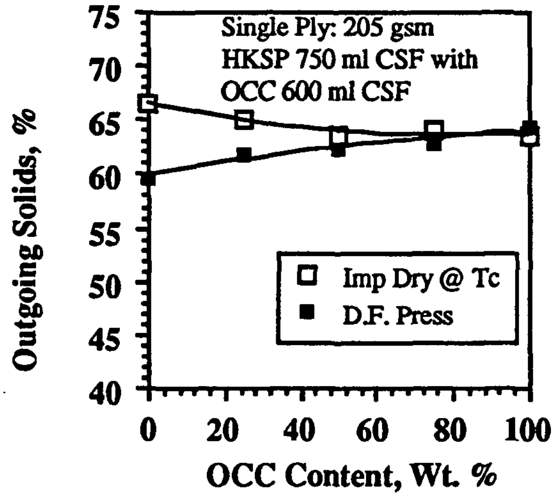

Figure 14. Outgoing solids vs. OCC content for impulse drying and double-felted pressing with blends of HKSP750 and OCC600.

Figures 15 and 16 show outgoing solids vs. top layer freeness for double-ply sheets where the two bottom layer blends are considered. When the bottom layer was made from a 50%:50% blend of HKSP750 and OCC600, impulse drying was superior to double-felted pressing independent of top layer freeness. For the case when the bottom layer was made from 100% OCC600, impulse drying was superior when the top layer freeness was more than 600 ml CSF.

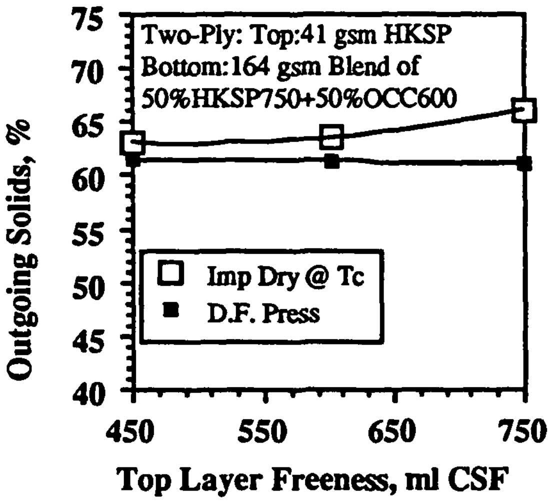

Figure 15. Outgoing solids vs. top layer freeness for impulse drying and double-felted pressing with bottom layer of 50%HKSP750 and 50% OCC600 with HKSP top layer.

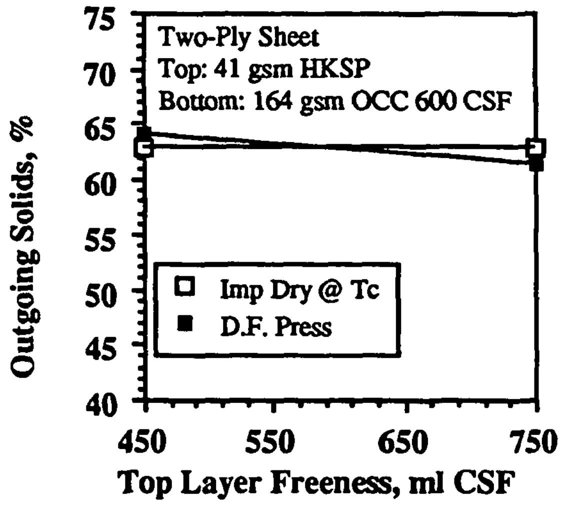

Figure 16. Outgoing solids vs. top layer for impulse drying and double-felted pressing with OCC600 bottom layer and HKSP top layer.

Many linerboard manufacturers use the cross direction STFI compression strength as the target strength parameter used to adjust their processes. Hence, the higher the CD STFI Index the better. Figures 17 and 18 show CD STFI Index vs. OCC content for single-ply sheets made from high Kappa southern pine and old corrugated containers. In Figures 13 and 14, it was observed that impulse drying dryness was superior to double-felted pressing dryness for OCC content below 60%. In Figures 17 and 18, impulse drying CD STFI Index was superior to that of double-felted pressing as long as OCC content was below 50%. Comparing the CD STFI Index obtained by impulse drying to that of the control shows that impulse drying has a benefit over conventional papermaking independent of OCC content.

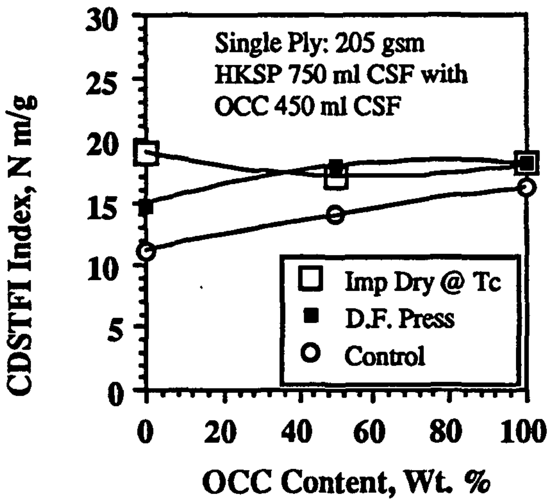

Figure 17. CD STFI Index vs. OCC content for impulse drying and double-felted pressing with blends of HKSP750 and OCC450.

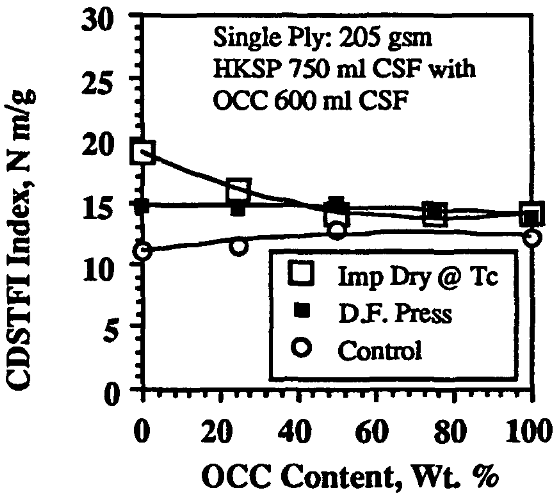

Figure 18. CD STFI Index vs. OCC content for impulse drying and double-felted pressing with blends of HKSP750 and OCC600.

Figures 19 and 20 show CD STFI Index vs. top layer freeness for double-ply sheets. When the bottom layer was made from a 50%:50% blend of HKSP750 and OCC600, impulse drying CD STFI Index was superior to that of double-felted pressing when top layer freeness was greater than 550 ml CSF. When the bottom layer was made from 100% OCC600, impulse drying CD STFI Index was equal or superior for the entire range of top layer freeness. Observe that impulse drying always resulted in superior strength as compared to the control.

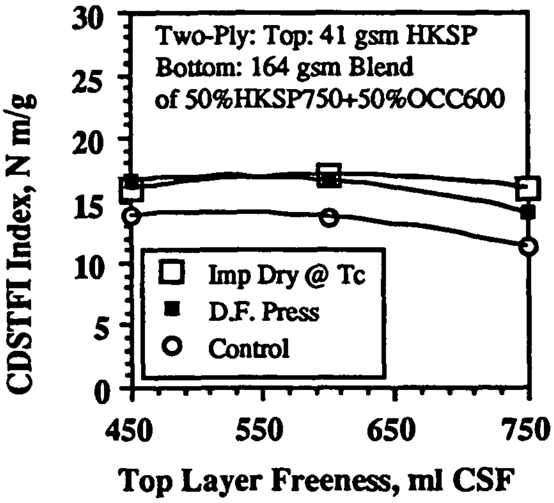

Figure 19. CD STFI Index vs. top layer freeness for impulse drying and double-felted pressing with bottom layer of 50%HKSP750 and 50%OCC600 with HKSP top layer.

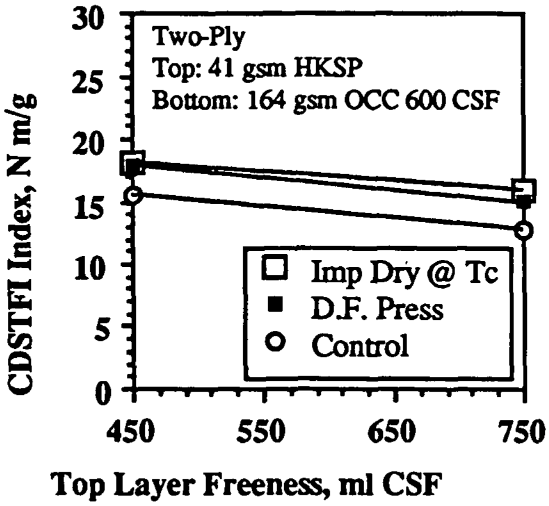

Figure 20. CD STFI Index vs. top layer for impulse drying and double-felted pressing with OCC600 bottom layer and HKSP top layer.

CONCLUSIONS

Preliminary experiments identified procedures for operating the Formette Dynamique to achieve the correct fiber orientation and to map out the influence of refining on fiber morphology and sheet permeability. The major result of these preliminary experiments was to show that Z-directional permeability is nearly independent of fiber orientation in the sheet while being strongly dependent on refining. In particular, the refining effect on permeability was found to be species dependent in that Douglas fir was less permeable to water transport than was southern pine at high freeness levels. This in turn, was traced to the higher fines concentration of the Douglas fir.

In the first experimental group, single-ply 42 lb liner made from five minimally refined furnishes were impulse dried to explore the influence of fiber species and lignin content on impulse drying. In these experiments, high and low Kappa southern pine and Douglas fir were evaluated, as was a OCC furnish. The major conclusions of this part of the work were that Kappa number had little effect on impulse drying performance, while southern pine was found to have an advantage over Douglas fir. As a result of southern pine having lower fines concentration at high freeness, it could be impulse dried at higher temperatures resulting in higher outgoing dryness and enhanced physical properties.

The second group of experiments was designed to answer the question of how much recycled fiber could be blended with virgin Kraft and still be successfully impulse dried. Here, the criterion for success was that the strength and dryness imparted by impulse drying be superior to that which could be achieved by conventional double-felted pressing at the same impulse as used during impulse drying. In these experiments, single-ply sheets were formed from blends of OCC refined to two different freenesses with a lightly refined virgin southern pine. Southern pine was chosen based on the results of the first group of experiments. The general conclusion of the second group of experiments was that the strength advantage of impulse drying was observed at recycle concentrations of 50 percent or less, while a dryness advantage was observed for blends having recycle concentrations of 75 percent or less.

In the third group of experiments, two-ply sheets of various constructions were impulse dried to determine how the composition of the top and bottom layer influences optimum impulse drying operating conditions and resulting dryness and physical properties. The major conclusion was that the composition of that part of the sheet in contact with the heated surface controls the critical impulse drying temperature. When the bottom sheet was composed of 50 percent virgin Kraft and 50 percent recycled fiber, superior impulse drying dryness and physical property development were observed for top sheet compositions having freenesses of 450 ml CSF or more. Sheets constructed with a bottom sheet of recycled fiber and a top sheet of virgin Kraft showed enhanced dryness and strength as long as the heated surface of the sheet had a freeness of 600 ml CSF or more.

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